INSTRUCTION BOOK

for

BALLANTINE MODEL 440
SELBY* MICROPOTENTIOMETER

*MR. MYRON C. SELBY OF NATIONAL BUREAU OF STANDARDS, BOULDER, COLORADO

Manufactured by

BALLANTINE LABORATORIES, INC.

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WARRANTY

Ballantine warrants that each Model 440 will be suitable for calibration by the National Bureau of Standards.

Each Ballantine Laboratories, Inc. instrument, or part thereof, is warranted to be free from defects in material and workmanship. Ballantine Laboratories, Inc. obligation under this warranty is limited to repairing or replacing any instrument or part thereof, except vacuum tubes and thermocouples, which shall within one year after shipment to the original purchaser prove upon Ballantine Laboratories, Inc. examination to have become defective.

INSTRUCTION BOOK
FOR
BALLANTINE MODEL 440 SELBY MICROPOTENTIOMETER

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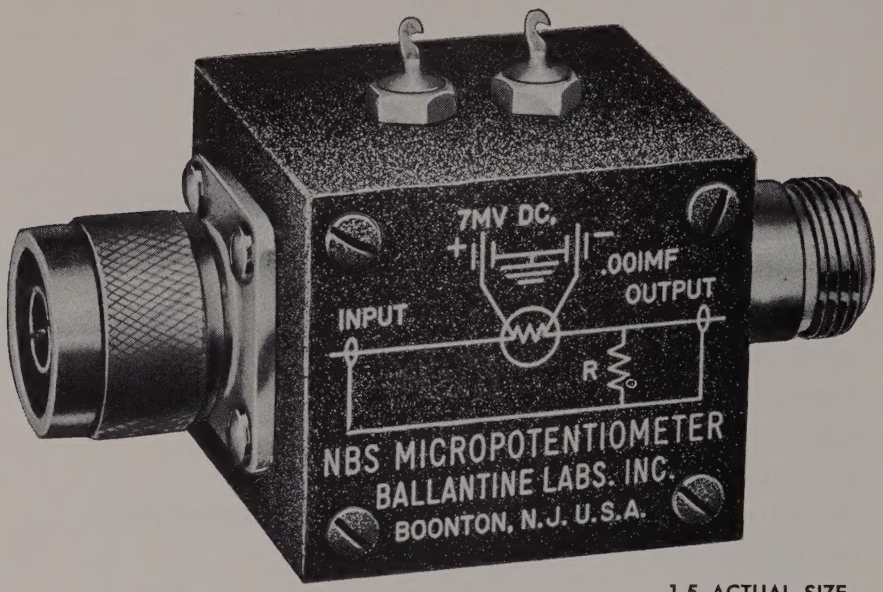
ADDITIONAL INFORMATION

A paper entitled "Techniques and Errors in High Frequency Voltage Calibration" by Dr. Endel Uiga and Wallace F. White is attached to and made a part of this instruction book.



1.5 ACTUAL SIZE

Figure 1 — Ballantine Model 440 Selby Micropotentiometer

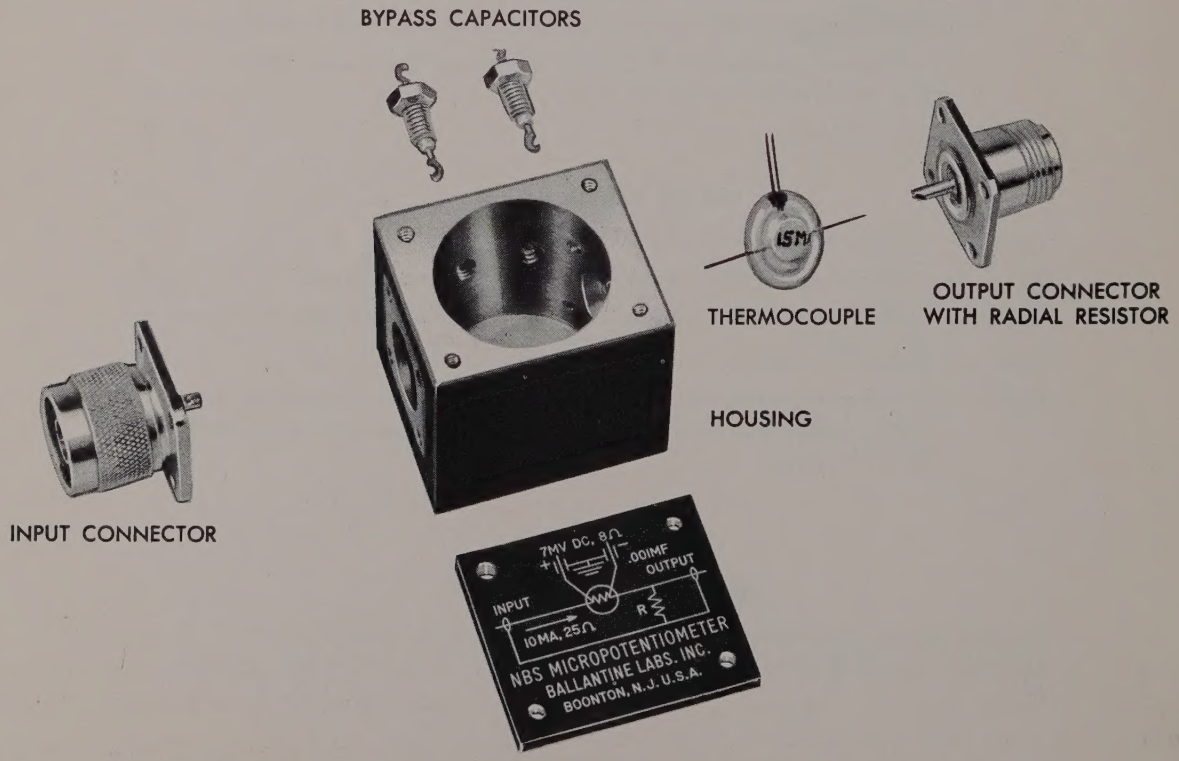


Figure 2 — Ballantine Model 440 Selby Micropotentiometer, Exploded View

1. SPECIFICATIONS

Radial Resistors

Available in nominal values from .010 to 22 ohms with ±20% tolerance. Each resistor is supplied soldered in Type N female coaxial connector.

Housings

Normally supplied with either a 5, 10 or 15 mA UHF-type thermocouple. Higher thermocouple ratings available on request.

Voltage Range

17 microvolts to 0.4 volt dependent on combination of radial resistor and thermocouple selected. Each combination will have a nominal output voltage equal to the product of resistance and rated thermocouple current, and can be varied from 1/3 to 1-1/3 of this nominal output.

Outputs greater than 0.4 volt can be obtained by using higher thermocouple ratings. For example, a 50 mA thermocouple with a 22 ohm resistor will produce outputs from 0.37 to 1.4 volts.

Frequency

DC to 900 megacycles.

Accuracy

As of December, 1961, the accuracies quoted on calibration certificates from the NBS Calibration Center, Boulder, Colorado, are 2% at 5 Mc, 3% 100 Mc to 400 Mc, and 5% 500 Mc to 900 Mc. Users of Micropotentiometers should check with NBS from time to time regarding any change in these figures.

Calibration and Certification

Model 440 Micropotentiometers may be calibrated and certified by the National Bureau of Standards Calibration Center, Boulder, Colorado, at frequencies up to 900 Mc. Because of the heavy work load at NBS, Ballantine has agreed to provide calibration and certification for each Radial Resistor/Thermocouple combination at the following frequencies: 5 Mc, 100 Mc, 300 Mc, 400 Mc, and 500 Mc.

Ballantine calibration and certification accuracies will be based on the accuracies of *special standards supplied for this service by NBS.* It is expected that the additional uncertainty introduced by the Ballantine calibration will not exceed 1% up to 500 Mc.

Calibration from 500 Mc to 900 Mc by Ballantine may be supplied sometime during 1962 but during the early part of 1962 such calibrations should be obtained from NBS, Boulder, Colorado. Please check with Ballantine during 1962 regarding this service.

2. PURPOSE

The Ballantine Model 440 Micropotentiometer is designed to provide a precisely determined voltage at its output terminal when dc to 900 megacycles current is fed into the input terminal. The input current flows through a UHF-type thermocouple to a radial resistor of known constant value. The voltage developed across the resistor becomes the standard which can be used to calibrate electronic voltmeters, oscilloscopes, signal generators and other devices.

The Model 440 is manufactured by Ballantine Laboratories based on designs by Mr. Myron C. Selby of the National Bureau of Standards, Boulder, Colorado. It is licensed under patents of the U. S. Government.

3. DESCRIPTION

Figure 1 shows the complete Model 440 Micropotentiometer assembly. Figure 2 is an exploded view showing the housing with a Type N male coaxial input connector, a UHF-type insulated thermocouple for monitoring the input current, screwdriver, and plugged into any other housing carrying a thermocouple of a different rating. If, for example, we use a 0.02 ohm radial resistor and a 5 milliampere thermocouple it is possible to produce a standard voltage output of

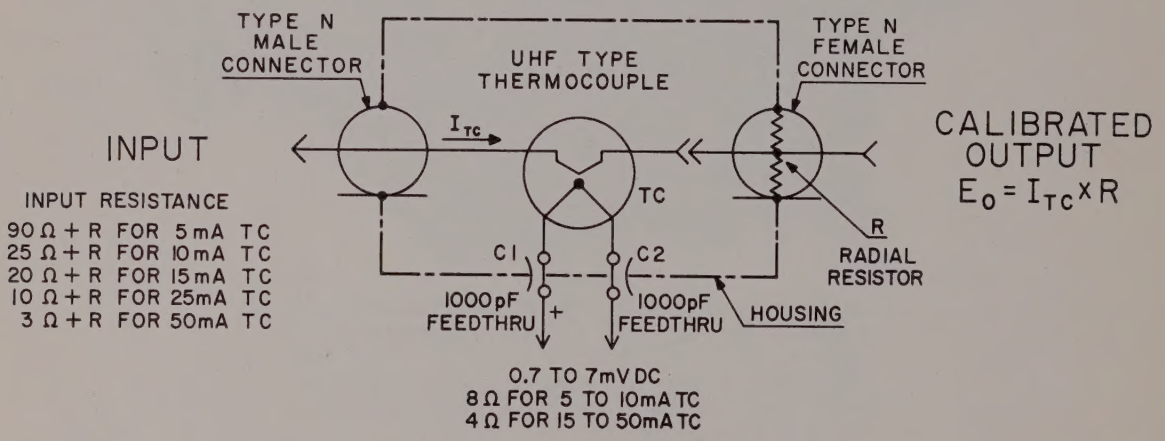


Figure 3 — Ballantine Model 440 Selby Micropotentiometer, Schematic Circuit Diagram

two feed-thru capacitors to provide leads to a dc microammeter, and a special radial resistor which is built into a Type N female coaxial output connector. Figure 3 is a schematic circuit diagram of the instrument.

Construction of the radial resistor is most important, and special techniques must be used to make one whose resistance remains nearly constant from dc to beyond 500 Mc. If the current provided by an external signal generator is maintained constant, as indicated by a constant thermocouple output read on an external dc microammeter, the voltage drop across the radial resistor can be used as a precision low impedance source of voltage whose output remains constant from dc to beyond 500 Mc.

The nominal output voltage of a Model 440 is given by the product of the heater current rating of the thermocouple and the resistance of the radial resistor. This voltage can be varied from one-third to one and one-third of full rated output by varying the thermocouple current over a four-to-one range. To provide additional voltage ranges, any radial resistor can be easily removed with the aid of a 100 microvolts for 5 milliamperes current, and 40 microvolts for 2 milliamperes current. Higher resistor values of 22 ohms, and thermocouples rated to 15 milliamperes may be used to produce voltages to approximately 0.44 volt. It is possible to use a 50 mA thermocouple with a 22 ohm radial resistor to obtain 1.4 volts provided the signal generator feeding the micropotentiometer is capable of supplying this amount of current.

Additional laboratory standard devices made by Ballantine are the Model 390 A-T Voltmeter designed to measure voltages from 1 volt to 300 volts in the frequency range from 10 Mc to 1000 Mc, and the Model 393 High Frequency Transfer Voltmeter designed to measure voltages from 1 volt to 50 volts in the frequency range of 25 cps to 30 Mc. These are also based on NBS designs. A laboratory equipped with Model 440 Micropotentiometers for low voltages, Model 390 for high voltages, and Model 393 for high voltages at higher accuracy up to 30 Mc, will have a wide voltage range as well as a wide frequency range in its laboratory basic ac voltage standards.

4. OPERATION AND APPLICATIONS

The Model 440 Micropotentiometer is ready for use as received. It is necessary only to connect the input to a source capable of delivering the required current over the frequency range desired, and to attach a suitable dc microammeter to the thermocouple output. The Micropotentiometer is then ready to serve as a precision source of low-level, high-frequency voltage.

CAUTION . . . When making connections to the output connector avoid excessive strains on the center conductor to prevent damaging the radial resistor.

The rf output voltage of the Micropotentiometer, at any frequency, is given by the product of the thermocouple current, whose magnitude is indicated by the dc couple output, and the calibrated impedance of the radial resistor. Normally a Micropotentiometer will reproduce the same output voltages for long periods of time. However, the value of the radial resistor may change due to aging effects and the relationship of thermocouple heater current to dc couple output may change as the result of momentary overloads. The Micropotentiometer output, however, can always be standardized at either dc or low-frequency ac where accurate milliammeters and voltmeters are readily available. Within its specified range the Micropotentiometer will then reproduce this voltage at high frequencies with an accuracy as shown on the Test Report. Standardization should be carried out at the ambient temperature at which the Micropotentiometer will be operated, or an additional error due to the temperature coefficient of the thermocouple will be introduced. In all cases, allow the thermocouple at least 10 minutes of operation at the desired current level to produce complete temperature stabilization.

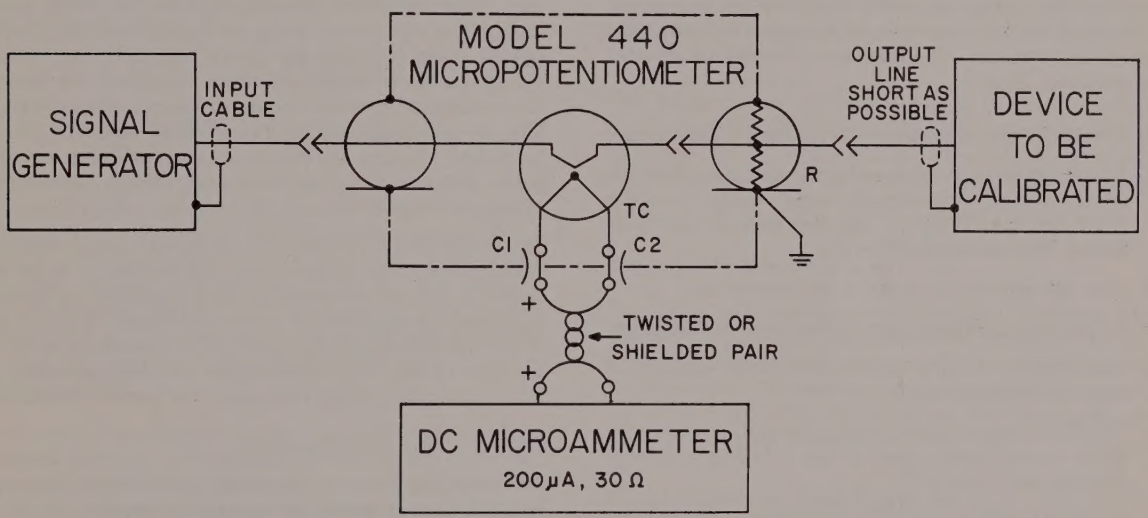


Figure 4 — Typical Test Setup

CAUTION . . . Continuous current overloads of greater than 50%, or momentary overloads of more than 100%, can ruin or seriously alter the thermocouple characteristics.

Figure 4 shows a typical test setup using a Model 440 Micropotentiometer. One application of the Model 440 Micropotentiometer is in the calibration of sensitive high-frequency voltmeters. The Model 440 may be used to check

the frequency response of voltmeters, relative to some reference frequency, or by calibrating the Micropotentiometer output against auxiliary standards at dc or low-frequency ac, it may be used as an absolute voltage standard. The Model 440 Micropotentiometer may also be used, in conjunction with an auxiliary transfer device, to calibrate the appropriate output levels of signal generators over a wide frequency range. Because the radial resistance is of a low value and securely soldered into a Type N coaxial connector, Micropotentiometers are useful devices whenever a stiff, well-shielded, high-frequency voltage source is required.

FOR USE AS A RELATIVE VOLTAGE STANDARD, 0-900 Mc (to check frequency response of voltmeters, oscilloscopes, etc. For example, to calibrate the frequency response of a vacuum tube voltmeter in terms of an arbitrary reference level.)

1. Adjust the signal generator to a reference frequency.
2. Adjust the level of the signal generator to produce the desired Micropotentiometer output voltage into the voltmeter. **CAUTION . . . Do Not Exceed 150% of Rated Thermocouple Current.**
3. Note the indication on the dc microammeter.
4. Adjust the signal generator to a new desired frequency.
5. Adjust the level of the signal generator to produce the same current as in Step 3.
6. The Micropotentiometer output voltage into the voltmeter is now maintained at the arbitrary reference level selected in Step 2.
7. Repeat Steps 4 - 6 as required for each frequency.

FOR USE AS AN ABSOLUTE VOLTAGE STANDARD, 0-900 Mc (to calibrate voltmeters, oscilloscopes, etc.)

1. Replace the signal generator in Figure 4 with a dc or low-frequency source.
2. Replace the voltmeter to be calibrated with a standard voltmeter (dc or ac, as selected in Step 1) having the correct voltage range and sufficient accuracy to measure the desired Micropotentiometer output voltage.
3. Adjust the level of the input until the standard voltmeter indicates the desired Micropotentiometer output voltage.
4. Note the indication on the dc microammeter.
5. Replace the dc or low-frequency source with a signal generator covering the desired frequency range.
6. Replace the standard voltmeter with the voltmeter to be calibrated.
7. Adjust the level of the signal generator until the dc microammeter indicates the same current as in Step 4.
8. The Micropotentiometer output voltage into the voltmeter is now maintained at the absolute level selected in Step 3.

Device To Be Calibrated (See Figure 4)

Certain precautions are necessary if the device to be calibrated is to respond as desired to the Model 440 output voltage. The input resistance of the device should not load the Micropotentiometer, and the input capacitance should be small to minimize the transmission-line effect discussed below. The capacitance should be measured at the frequencies at which the measurements are to be made, rather than relying on a low-frequency value, because the two will often be considerably different.

In addition, consideration should be given to the effects of ground currents, even if an isolation transformer is being used. Any impedance existing between the input ground terminal of the device being calibrated, and the internal ground point to which the device responds (for example, the ground of the input tube of an amplifier) can serve, in the presence of ground current, to inject in series with the Micropotentiometer output an additional unknown and uncontrolled voltage. Correct grounding practices are absolutely necessary if a high-frequency voltage calibration is to be meaningful.

The purity of the waveform of the input signal is discussed below titled, "Signal Generator". If the device to be calibrated is true rms-responding, there should be no problem regarding the waveform of the source signal. If it is a peak or average-responding type of VTVM, waveform of the input signal is very important for precision measurements. Refer to paragraph "Signal Generator" for further information.

Output Cable (See Figure 4)

The output cable that connects the Model 440 to the device being calibrated should be as short as possible and in the form of a shielded coaxial cable to minimize ground current, pickup, and transmission-line effects.

If a length of coaxial cable is terminated in its characteristic impedance, the voltage along the cable will be constant and equal to the impressed voltage. If the cable is terminated in any impedance other than its characteristic impedance, the voltage along the cable will vary as a function of the terminating impedance, the characteristics and length of the line, and the frequency. Figure 5 shows the relationship of

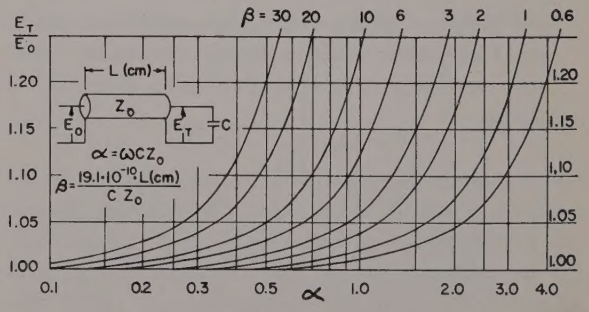


Figure 5 — This family of curves shows the relationship between the voltage at the flange of the output connector of the Model 440 and the voltage existing at distances from this point.

output voltage to impressed voltage for a section of transmission line terminated in a capacitance. For other terminations similar curves can be derived from standard transmission-line equations.

As an example of the transmission-line effect, assume a high-frequency voltmeter to be connected to a Micropotentiometer by means of a coaxial adapter. The total length from the flange of the Micropotentiometer to the output tip of the adapter is 2 inches. The voltmeter is to be calibrated at a frequency of 250 Mc where its input shunt resistance is 1000 ohms and shunt capacitance is 6.4 pF (micro-micro farads). The shunt resistance can be neglected since it is large compared to the capacitive reactance. Using the formulas shown on Figure 5:

$$\alpha = \omega C Z_0 = 2\pi\,(250 \times 10^6)\;(6.4 \times 10^{-12})\;(50) = 0.5$$

$$\beta = \frac{19.1 \times 10^{-10} L(\text{cm})}{C Z_0} = \frac{19.1 \times 10^{-10}\;(2 \times 2.54)}{(6.4 \times 10^{-12})\;(50)} = 30.4$$

Figure 5 then shows that the voltage appearing at the tip of the output UHF connector will be 20% higher than the calibrated output voltage of the Micropotentiometer. If the length of cable can be reduced to a length of approximately 0.4 inches, the error will be reduced to 3%. This example demonstrates the large errors that can occur at high frequencies due to the transmission-line effect, and illustrates the need for extremely short interconnections as the frequency increases.

Short interconnections are also necessary to reduce the effects of ground currents. *Circulating ground currents of various frequencies exist in any system of interconnected electronic equipment connected to a common power line.* If any appreciable impedance exists in the ground connection between the Micropotentiometer and the devices being calibrated, these currents will produce a voltage drop across the impedance which is injected in series with the Micropotentiometer output to the device. At the microvolt and millivolt level such extraneous signals can produce large errors. The ground impedance may be resistive, due to poor electrical connections, or excessive lead length, or inductive due to lead length, or failure to use coaxial cable and connectors.

The effects of ground currents can often be substantially reduced by using an isolation transformer. This transformer may be introduced in the power line of either the generator or the device being calibrated, where it must exhibit small coupling to high-frequency signals.

The output cable from the Model 440 must also be adequately shielded to prevent pickup of high-level signals in the low-level Micropotentiometer output.

DC Microammeter (See Figure 4)

A dc microammeter is required to monitor the rf thermocouple heater current by responding to the dc output of the couple. The absolute accuracy of this indication is of secondary importance. It is important that the microammeter be stable, easily read and reset to a reference value, and of correct sensitivity to indicate near full-scale current for rated thermocouple heater current.

All thermocouples used in the Model 440 have a nominal 7 millivolt open-circuit dc output for rated heater current. The 5 mA and the 10 mA type thermocouples have a dc output resistance of 8 ohms; the 15 mA unit has 4 ohms. For the microammeter to indicate full-scale for rated heater current, the product of full-scale microammeter current times the total dc circuit resistance should equal 7 millivolts. The total circuit resistance is the sum of the couple resistance (either 4 or 8 ohms), the meter resistance, and any added series resistance.

As an example, for a 10 milliampere thermocouple with an 8 ohm couple resistance, we could use a 200 microampere full-scale meter having 10 ohms resistance by adding a series resistance of 17 ohms. Then $200 \times 10^{-6}\;(8 + 10 + 17) = 7 \times 10^{-3}$, as required.

The dc output of the Model 440 is available at the terminals of two high-frequency by-pass capacitors. The connection of the dc microammeter should be made by either a shielded, twisted pair or a coaxial cable to prevent possible pickup of low-frequency fields.

Input Cable (See Figure 4)

The input cable that connects the signal generator to the Model 440 may be of any convenient length. It should be a shielded cable to avoid leakage of the high-level generator output into the low-level Micropotentiometer output circuit. At the Micropotentiometer end, the cable should be terminated in a Type N female connector.

Signal Generator (See Figure 4)

The signal generator used to supply thermocouple heater current to the Model 440 must meet several requirements. Naturally it must be capable of delivering the desired current to the resistance provided by the thermocouple heater, and it must do so over the entire frequency band of interest. In addition, the generator must supply this current with minimum distortion.

The Model 440 is an rms-responding device because it uses a thermocouple to monitor the current that flows thru the radial resistor. If the device which is being calibrated at the output of the Micropotentiometer is also rms-responding, distortion in the waveform of the current supplied by the signal generator will have no effect on the accuracy of the calibration. However, if the device being calibrated is average or peak-responding, distortion in the waveform will cause an error in calibration. The amount of this error is proportional to the magnitude of the harmonics present and their phase relationship to the fundamental.

It may be difficult to measure adequately the distortion in the generator output at high frequencies. Oscilloscopes may be used for a visual indication, and an rf distortion meter may be valuable. The use of additional tuned circuits or coaxial low-pass filters between the generator and Micropotentiometer should also be considered as a means of reducing the error produced by the waveform if such distortion is suspected.

5. GENERAL DISCUSSION OF WAVEFORM vs. ACCURACY OF ELECTRONIC VOLTMETERS

Electronic voltmeters may be classified into three groups according to the way in which they respond to the input signal. In the first group are those instruments that measure the average value of the ac voltage. In most cases, the scale of the indicating meter of these instruments is calibrated to read in terms of the rms value of a sinewave. In the second group are the instruments that respond to the peak value of the ac voltage. All instruments having a diode rectifier at their input are included in this classification. Here again the scale calibration is usually in terms of the rms value of a sinewave. In the third group are the instruments, such as the Ballantine Models 320 and 350, that respond to the actual rms value of the ac signal regardless of its waveform.

If a wave under measurement is a pure sinewave, the indicated rms values of all three groups of instruments will be the same. However, if the wave under measurement has harmonic or unwanted frequencies, the different groups of voltmeters will respond differently. In all cases the average-responding meters will give a much truer indication of the rms of the fundamental alone, or of the rms of the fundamental plus the harmonic, than the peak-responding-type meters. Of course the true rms VTVM will be the most accurate of all when used to measure complex waveform voltages.

The amount of error introduced by a harmonic is a function of both its magnitude and its harmonic phase relationship. The following table compares the errors of two types of voltmeters in the rms indications of waves with various harmonics whose amplitude is 20% of the fundamental and whose phasing is such as to produce maximum error in each case.

The Model 440 Micropotentiometer is used to measure the true rms voltage regardless of the waveform of the input signal. If an average-responding or a peak-responding voltmeter is being calibrated it is essential that a pure sinusoidal signal be fed to the Micropotentiometer because this type of signal is the one on which the calibrations are based. If a true-rms voltmeter is being calibrated the waveform of the signal is no importance.

Form of Wave	*RMS Value of Fundamental*	*RMS Value of Fundamental plus Harmonic*	*Maximum Error in Indicated RMS Compared with RMS of Fundamental*	
			Peak Responding Meter	*Average Responding Meter*
Pure Sine	1.	1.	0	0
Sine Plus 20% 2nd Harmonic	1.	1.02	20%	1.9%
Sine Plus 20% 3rd Harmonic	1.	1.02	20%	6.7%
Sine Plus 20% 4th Harmonic	1.	1.02	20%	1.7%
Sine Plus 20% 5th Harmonic	1.	1.02	20%	4.0%

APPENDIX

VOLTAGE COVERAGE WITH DIFFERENT RADIAL RESISTOR-THERMOCOUPLE COMBINATIONS

The recommended range of voltage coverage for each Radial Resistor-Thermocouple combination is approximately four to one, that is, from approximately 35% above rated thermocouple current to 33% of rated thermocouple current. Thus a Radial Resistor of 0.10 ohms and a Thermocouple rated at 10 milliamperes may be operated between 330 and 1350 microvolts. A tabulation of the microvolt ranges for nominal values of Radial Resistors and for three Thermocouples is given in the table below.

Actual values of Radial Resistors will seldom have the exact nominal values shown in the table. If the Radial Resistor referred to above has 0.12 ohm instead of 0.10, the operating range with a 10 milliampere Thermocouple will be from 396 to 1620 microvolts.

The dc resistance of Radial Resistors will be ±20% of the nominal resistances shown in the table below. Each Radial Resistor is identified by a serial number, and by its accurate dc resistance marked on a metal foil attached to the unit.

See page 2 regarding possible use of thermocouples having higher ratings than shown in the table.

RADIAL RESISTOR (Nominal value in ohms)	MINIMUM - MAXIMUM VOLTAGE (μV)		
	5 mA THERMOCOUPLE	10 mA THERMOCOUPLE	15 mA THERMOCOUPLE
0.010	17 - 67	33 - 135	50 - 200
0.015	25 - 100	50 - 200	75 - 300
0.022	37 - 145	75 - 290	110 - 440
0.033	55 - 220	110 - 440	165 - 660
0.047	80 - 310	160 - 620	240 - 940
0.068	115 - 450	230 - 900	340 - 1,350
0.10	170 - 670	330 - 1,350	500 - 2,000
0.15	250 - 1,000	500 - 2,000	750 - 3,000
0.22	370 - 1,450	750 - 2,900	1,100 - 4,400
0.33	550 - 2,200	1,100 - 4,400	1,650 - 6,600
0.47	800 - 3,100	1,600 - 6,200	2,400 - 9,400
0.68	1,150 - 4,500	2,300 - 9,070	3,400 - 13,500
1.0	1,700 - 6,700	3,300 - 13,500	5,000 - 20,000
1.5	2,500 - 10,000	5,000 - 20,000	7,500 - 30,000
2.2	3,700 - 14,500	7,500 - 29,000	11,000 - 44,000
3.3	5,500 - 22,000	11,000 - 44,000	16,500 - 68,000
4.7	8,000 - 31,000	16,000 - 62,000	24,000 - 94,000
6.8	11,500 - 45,000	23,000 - 90,000	34,000 - 135,000
10.	17,000 - 67,000	33,000 - 135,000	50,000 - 200,000
15.	25,000 - 100,000	50,000 - 200,000	75,000 - 300,000
22.	37,000 - 145,000	75,000 - 290,000	110,000 - 440,000

UHF THERMOCOUPLES

Ballantine Part No.	Milli-amperes Rating	Approx. Resistance of Couple Circuit (ohms)	Approx. Resistance of Heater Circuit (ohms)
2951	5	8	90
2952	10	8	25
2953	15	4	20
2954	25	4	10
2955	50	4	3

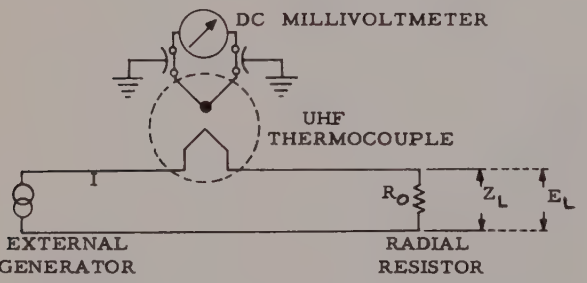
The thermocouples used in Model 440 Micropotentiometers are UHF units manufactured by Best and are available from Ballantine.

ADDITIONAL NOTES CONCERNING THE CORRECTIONS FOR LOADING ERRORS WHEN USING MODEL 440 MICROPOTENTIOMETERS

In the past, some confusion has existed in the use of Micropotentiometers having radial resistors of 1 ohm or higher because of the increased importance of loading errors. This note will discuss the problem and describe how loading errors can be computed and their effect compensated.

Loading errors exist when an external load Z_L is small enough to shunt part of the thermocouple current I that normally flows through radial resistor R_O under open-circuit conditions. The effect is to change the voltage E_L across the load from that value determined by the product of I and R_O. Loading errors must be considered not only when a Micropotentiometer is used as a *relative* voltage source, in determining the frequency response of some device, but also when an *absolute* voltage calibration is desired.

The circuit is as follows:



$$E_L = I \frac{R_O Z_L}{R_O + Z_L}$$

Where E_L is the load voltage for a thermocouple current I

$$= E_O \frac{Z_L}{R_O + Z_L}$$

Where E_O is the open-circuit output voltage for a thermocouple current I

$$\text{or } E_O = E_L \left(1 + \frac{R_O}{Z_L}\right)$$

If $R_O << Z_L$, then E_L (the voltage delivered to the load) will equal E_O (the Micropotentiometer open-circuit output voltage) and there will be no loading error.

Notice that the loading effect need not be resistive. At higher frequencies it will also be necessary to measure the reactive part of Z_L to determine if loading errors are present.

In addition, at higher frequencies another effect enters into the loading error. If Z_L is connected to the Micropotentiometer output by a length of transmission line (which is always the case in practice), Z_L will be tranformed to an equivalent Z_L' at the Micropotentiometer output. It is this value Z_L', determined by Z_L, the transmission line characteristics, and the frequency, which must be used in determining the loading error according to the above equation.

Other errors, both at low and high frequencies, are discussed in the Model 440 Instruction Book as well as in "Techniques and Errors in High-Frequency Voltage Calibration," Uiga and White, IRE Trans. on Inst., Vol. 1 - 9, No. 2, Sept. 1960. The latter paper is supplied with each instruction book for the Model 440.

REFERENCES OF VALUE

1. "Application of RF Micropotentiometers for Calibration of Signal Generators to 1000 Mc" by L. F. Behrent in National Bureau of Standards Technical Note No. 37 distributed by U. S. Dept. of Commerce, Office of Technical Services, Washington 25, D. C. Price 50 cents.

2. "Accurate Radio-Frequency Microvoltages" by Myron C. Selby in Communications and Electronics, AIEE 6: 158-164 (May, 1953).

3. "Techniques and Errors in High Frequency Voltage Calibration" by Uiga and White in IRE Transactions on Instruments, Vol. 1-9, No. 2, Sept., 1960. This paper is supplied with each copy of this instruction book. Additional copies will be sent on request at no charge.

Techniques and Errors in High Frequency Voltage Calibration

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Abstract

A group of high-frequency voltage standards has been developed by the National Bureau of Standards to serve as transfer devices between NBS standards and working instruments. The series consists of A-T Voltmeters, Thermal Voltage Converters, and Micropotentiometers.

This paper discusses the techniques and errors involved in applying these devices to typical problems such as the calibration of electronic voltmeters. Possible sources of errors included are human error, loading effects, voltage drop in connecting leads, stray field pickup, effect of ground currents of signal and power frequencies, transmission-line effects, response and waveform errors.

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Techniques and Errors in High-Frequency Voltage Calibration*

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A TRUE volt can be derived from an electromagnetic or electrostatic definition, but, for all practical and legal purposes, the volt has a value which the National Bureau of Standards describes and certifies. The task is then to transfer that volt to working standards and apply it to our instruments. Unfortunately, during this process the volt deteriorates somewhat. The reasons for this are:

1) Limited precision of working standards.
2) Limited stability of working standards.
3) Calibration errors.

This paper is concerned mainly with the calibration errors that can occur when one is using micropotentiometers, HF transfer standards, and A-T voltmeters as working standards for HF voltage calibrations.

All three of the voltage standards have much in common and are susceptible to the same calibration errors. For one thing, they all use insulated-type vacuum thermocouples as stable HF devices whose dc output is not affected by the frequency of the ac heater current. Also, they all depend on the HF performance of capacitive-type attenuators or stable resistors. And further, they all transfer an HF measurement problem, by means of the thermocouples, to a more simple dc measurement.

Micropotentiometers are stable sources of low-level, HF voltage generated by a known thermocouple current flowing through a small known resistor. The current is derived from a laboratory generator and is maintained constant for all frequencies by monitoring the thermocouple dc output with an external millivoltmeter. The resistor is made frequency insensitive by a specially constructed disk configuration. Commercial units have been built that range in output voltage from 50 μv to 0.25 volt and will maintain their voltage constant to ± 5 per cent from dc to 500 Mc and beyond.

HF transfer standards also consist of a thermocouple-resistor combination. Here a specially mounted rod-type resistor acts as an input device to generate a frequency insensitive current proportional to an unknown ac voltage. This current flows through the thermocouple and produces a certain dc output. The device is now transferred to a dc source which is adjusted until the dc thermocouple output indicates that the same current is flowing through the resistor and thermocouple. The dc voltage is measured by standard means and its value is the rms value of the unknown ac voltage. Such converters have been made to measure voltages from below 1 volt to 200 volts with accuracies of better than ± 0.25 per cent from dc to 30 Mc.

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A-T voltmeters work in much the same manner as thermal voltage converters. Here the input resistor is replaced by an adjustable waveguide-below-cutoff attenuator. This attenuator is always set so that a constant current flows through the thermocouple, as indicated by a constant dc thermocouple output. If the attenuation characteristic has been previously determined as a function of an indicated mechanical setting, the unknown voltage can be determined in terms of this setting and the frequency. Because the type of attenuator used appears as a capacitive device, A-T voltmeters do not have a flat response with frequency. Instead, their response is essentially 6 db/octave with the sensitivity increasing for higher frequencies. A-T voltmeters have been built which will measure voltages above 1 volt from 150 Mc to 500 Mc and beyond, and above 30 volts from 10 Mc up, to an accuracy of ± 1 per cent of the calibration accuracy.

The most common calibration errors when certifying and applying working standards are:

1) Human error.
2) Loading error.
3) Transmission error.
   a) Voltage drop in connecting lines.
   b) Stray field pickup.
   c) Transmission line effects.
4) Ground current error.
   a) Ground current of power frequency.
   b) Ground current of signal frequency.
5) Response and waveform errors.

1) *Human Error:* Besides possible misunderstanding of the calibration equipment and technique, the visual error of reading meters is of most concern. This error can be reduced to approximately 0.1 per cent when optical reading devices as shown in Fig. 1 are used. This device projects an enlarged image of the meter scale and pointer to a ground glass and so reduces operator fatigue and eliminates parallax error.

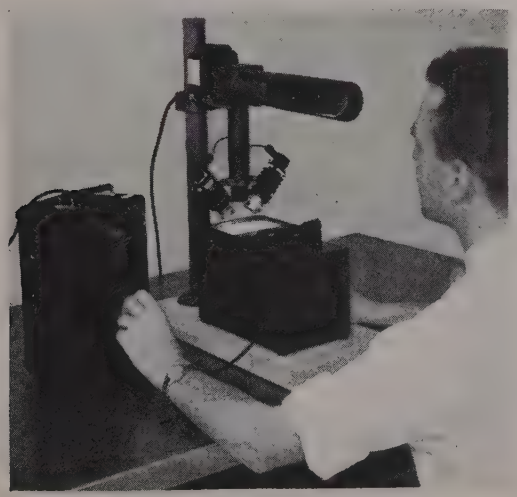


Fig. 1.

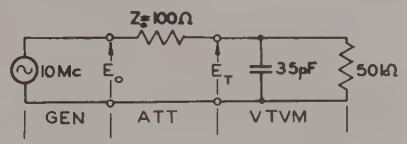
2) *Loading Error* is important when calibrated sources with known EMF, instead of terminal voltage, are used as standards. The drop in the source impedance causes the terminal voltage to be different from the EMF:

LOADING ERROR.

It should be noted when applying this formula that, in case of a VTVM, the real component of input impedance drops considerably at higher frequencies.

Example: A VTVM is calibrated at 10 Mc using a standard ladder attenuator with 100 ohms source impedance. The voltmeter impedance is 50 kilohms in parallel with 35 pf.

EXAMPLE:



$$E_T = \frac{Z_L}{Z_0 + Z_L} = E_0 \frac{Y_0}{Y_0 + Y_L}$$

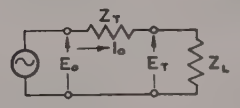
$$= E_0 \frac{10^{-2}}{10^{-2} + 2 \cdot 10^{-5} + j \cdot 6.28 \cdot 10 \cdot 10^6 \cdot 35 \cdot 10^{-12}} = \frac{E_0}{1.024}$$

Terminal voltage drops 2.4 per cent.

3) *Transmission Error* is the voltage difference between the calibrating voltage and the voltage at the input terminals of the instrument to be calibrated due to effects in the connection between the source and the instrument. Three sources of transmission error are discussed.

a) Voltage drop in connecting leads is negligible when high input impedance voltmeters are calibrated. However, at higher frequencies the leads should be as short as possible. The effect of a drop in the lead impedance is derived as follows:

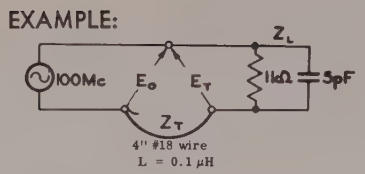
VOLTAGE DROP IN THE CONNECTING LEADS.



$$I_0 = \frac{E_0}{Z_T + Z_L} \approx \frac{E_0}{Z_L}$$

$$E_T = E_0 - I_0 Z_T = E_0 \left(1 - \frac{Z_T}{Z_L}\right)$$

Example: A voltmeter with an input impedance of 5 picofarads in parallel with 1 kilohm is connected to a 100-Mc calibration source. The ground connection is made over 4 inches of Number 18 wire which has an inductance of 0.1 μh.



$$E_T = E_0\left(1 - \frac{Z_T}{Z_L}\right) = E_0(1 - Z_T Y_L)$$
$$= E_0[1 - j6.28\cdot 100\cdot 10^6\cdot 0.1\cdot 10^{-6}(10^{-3} + j6.28\cdot 100\cdot 10^6\cdot 5\cdot 10^{-12})]$$
$$= E_0(1 + 0.197 - j\cdot 0.062) \approx 1.2E_0.$$

Terminal voltage rises 20 per cent.

b) Stray field pickup can occur in the loop formed by the connecting leads. The induced voltage (E) in a loop of area F (square inches) located in a field density B (gauss) is

$$E = 6.45\cdot B\cdot F\cdot \omega\cdot 10^{-8}.$$

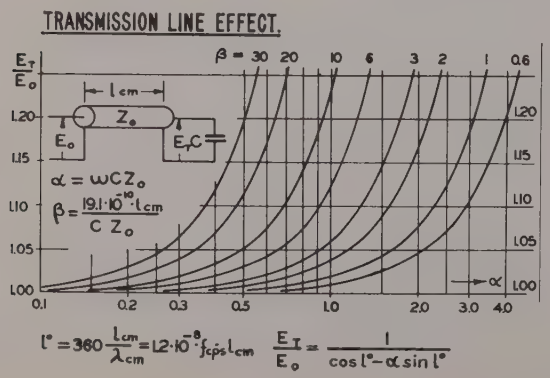
In case of a 60-cps field, the induced voltage is 2.4 mv /gauss and 100 square inches of loop area.

The typical stray field density under laboratory conditions is a fraction of a gauss at a normal laboratory bench, several gauss in the vicinity of a power transformer and tens of gausses close to a magnetically regulated transformer. The possible pickup from this source should be considered for low-level calibration work.

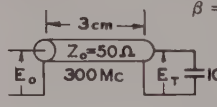
When HF fields are present in the laboratory, the condition is much more critical and every precaution should be taken to reduce the loop area as much as possible.

c) Transmission line effect: At frequencies above a few megacycles, the distance between the voltage source and instrument input terminals is not negligibly short compared to a wavelength. Therefore transmission line effects have to be considered, especially when the impedance of the voltage source interconnections and the input impedance of the device to be calibrated are not matched.

At higher frequencies the input impedance of most devices is capacitive. With this assumption, the following formula and curves can be derived from transmission line equations to find the voltage drop or rise in the line. The same result could be achieved with a Smith chart.



Example: A voltmeter with 10-pf input impedance has to be calibrated at 300 Mc by a micropotentiometer. A coaxial adapter with $Z_0 = 50\ \Omega$ of 3-cm length is needed between the input of voltmeter and the micropotentiometer. The transmission line error is

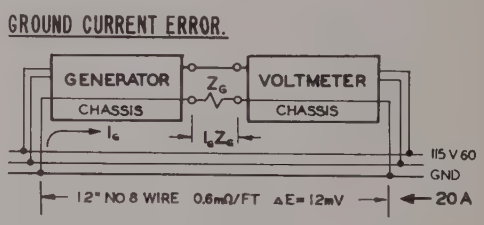


$$\alpha = \omega C Z_0 = 6.28\cdot 300\cdot 10^6\cdot 10\cdot 10^{-12}\cdot 50 = 0.94$$
$$\beta = \frac{19.1\cdot 10^{-10}\cdot 1}{CZ_0} = \frac{19.1\cdot 10^{-10}\cdot 3}{10\cdot 10^{-12}\cdot 50} = 11.4$$
$$\frac{E_T}{E_0} = 1.23$$

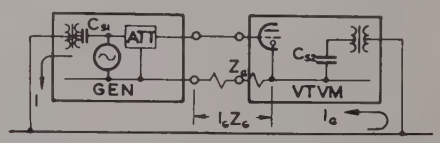
Voltage rises 23 per cent.

4) *Ground Current Error* occurs when currents of signal or power frequency flow in ground loops. These currents will cause an error because of the voltage drop in ground connections and because almost all voltmeters will respond more or less to ground currents.

a) Ground current of power frequency occurs when several grounds are used in a calibration setup. A typical situation is shown below.



b) The effects of ground currents of signal frequency are often the most difficult problems to consider with high frequency voltage calibrations. Their origin and mechanism are difficult to explain and trace. However, the ground currents can be measured with sensitive ammeters and their magnitude reduced to the very minimum. A typical picture of signal ground current is shown below.

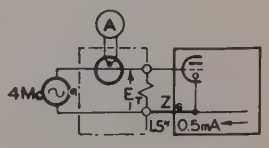


A ground loop is formed over the stray capacitances C_{s1}, C_{s2} and the power line with the internal oscillator E_0. A ground current I_G will flow which causes a drop $I_G \cdot Z_G$ in the ground impedance of the voltmeter. For example, a micropotentiometer is used to calibrate a 1-mv 4-Mc range of a voltmeter with regular binding posts as the input terminals. An 0.5-ma ground current is measured in the ground loop.

EXAMPLE:

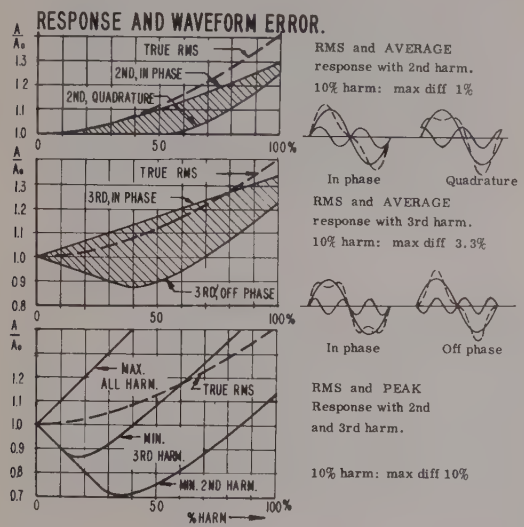
$E_T = 1mV \qquad L_G = 0.015\mu H$

$\Delta E_G = I_G Z_G$
$= 0.5\cdot 10^{-3}\cdot 6.28\cdot 4\cdot 10^6\cdot 0.015\cdot 10^{-6}$
$= 0.19\cdot 10^{-3} = 0.19$ mV



Possible error ±19 per cent.

5) Response and Waveform Error: When a nonsinusoidal calibration voltage is used and the response of the voltage standard is different from the response of the device under calibration, *i.e.*, calibration standard responds to rms value, the device to average value, a waveform error is possible. The difference in responses is shown in the following graph.[1]



In order to reduce the waveform and response error to approximately 1/10 of the calibration accuracy, the maximum distortion should be approximately 1/2 of the calibration accuracy when rms and average responses are compared and 1/10 of the calibration accuracy when rms and peak responses are compared.

A micropotentiometer and its schematic are shown in Fig. 2. Micropotentiometers are invaluable in the calibration of sensitive, wide-band voltmeters. In this application they replace the usual circuit of a level-monitor at the input of an adjustable attenuator. The uncertainty in the accuracy and stability of the level-monitor and the questionable frequency response of the attenuator, particularly for large attenuation ratios, are replaced by the known accuracy and response of a micropotentiometer.

Micropotentiometers, however, in common with the other working standards, are subject to the calibration errors discussed above. In particular, transmission, ground current, and response and waveform errors can seriously affect the accuracy of measurement. Fig. 3 shows a typical test setup using a micropotentiometer to calibrate a sensitive, wide-band voltmeter and will be used to illustrate these effects.

There are several loops where stray fields may induce a voltage large enough to affect the accuracy of the calibration. HF fields can enter the dc thermocouple circuit and affect the results by additional heating of the junction. For this reason, HF bypass capacitors are

[1] "Some effects of waveform on VTVM readings," *Hewlett-Packard J.*, vol. 6; April, May, June, 1955.

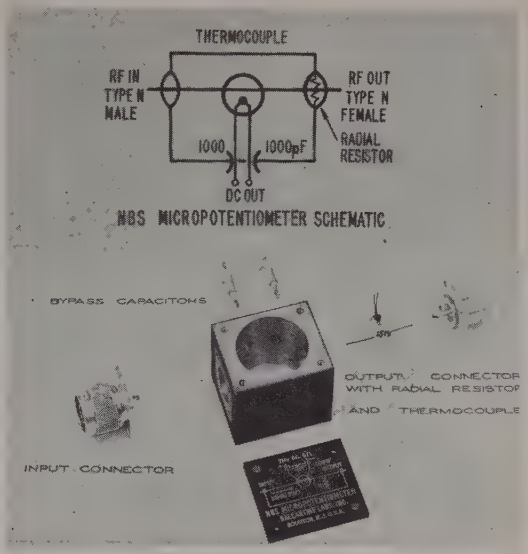


Fig. 2—NBS micropotentiometer.

Fig. 3.

used where the dc millivoltmeter leads enter the micropotentiometer housing and these leads are twisted and shielded. Since the internal thermocouple dc leads lie in a plane at right angles to the insulated RF heater circuit, there is little interaction between these two circuits. But stray fields, either of signal frequency or power-line frequency, can easily enter the loop formed by the micropotentiometer output resistor and the VTVM being calibrated. Therefore, this circuit should be made as short as possible and be adequately shielded.

For frequencies above 100 mc, the possible errors due to transmission line effects become important. Assume that the device to be calibrated has an input capacitance C and is connected to the micropotentiometer by a short length of coaxial cable. The curves shown under "transmission line effect" are a plot of the voltage rise at the end of the cable, relative to a constant micropotentiometer output, as a function of the cable char-

acteristics and the loading capacitance C. For other cable terminations, the error can be computed from transmission line equations. To minimize this error, the interconnecting cable should be made as short as possible. If the line can be terminated in a load close to its characteristic impedance, the errors will be substantially reduced.

The transmission line effect can be entirely eliminated if we use a length of lossless line between the micropotentiometer and the device being calibrated of exactly an integral number of half-wavelengths. Such a system would, of course, have to be readjusted for each new frequency.

Ideally we would like the grid-to-ground voltage at the input tube of the voltmeter to be a known fraction of the micropotentiometer output voltage. However, if an appreciable ac current is flowing over the ground system, there will be a voltage drop across any impedance that exists in the ground system between the micropotentiometer output connector and the input tube of the voltmeter. This voltage drop will be in series with the micropotentiometer output and will act as an additional voltage source. This voltage can easily cause errors of 5 per cent or more for micropotentiometer outputs in the microvolt or low-millivolt region.

To minimize this error three approaches are possible. First, the ground current itself can be reduced; second, the impedance across which the voltage drop is developed can be reduced; and third, the ground current can be diverted to another path. The first method is most easily accomplished by the addition of an isolation transformer. This transformer can be connected either in the signal circuit or in the power line. In either case, it must exhibit very small coupling between primary and secondary for signals of ground current frequency. For the second method of reducing the ground circuit impedance, it is necessary to shorten the interconnections between the micropotentiometer and the device being calibrated as much as possible. Coaxial connectors should be used rather than binding posts and banana plugs, and particular care must be taken of all connections, soldered or mechanical. For the third method, we must provide a path for the ground current other than through the equipment under test. This can be done by mounting the equipment on a conducting surface and running low-impedance grounding straps from this surface to the output ground of the micropotentiometer and the ground point of the VTVM.

A micropotentiometer is an rms-responding device, since it depends on the heating effect of the RF current through the thermocouple. In many cases the resulting output voltage will be used to calibrate average or peak-responding instruments. Consideration must be given, therefore, to waveform errors. For example, a sine wave with 20 per cent third harmonic will cause a 2 per cent change in rms indication relative to the rms value of the fundamental alone. Such a signal can produce, depending on the phase relationship, an error as large as 6.7 per cent in the average-responding device, and make a peak device read 20 per cent in error.

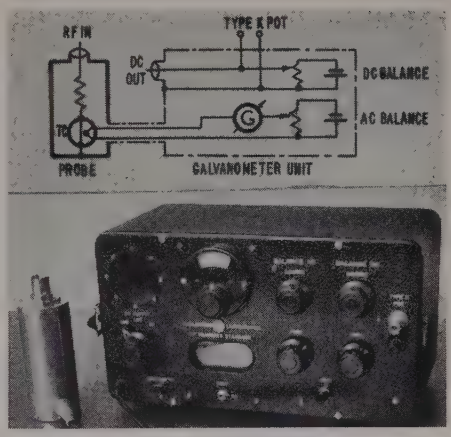


Fig. 4—HF transfer standard.

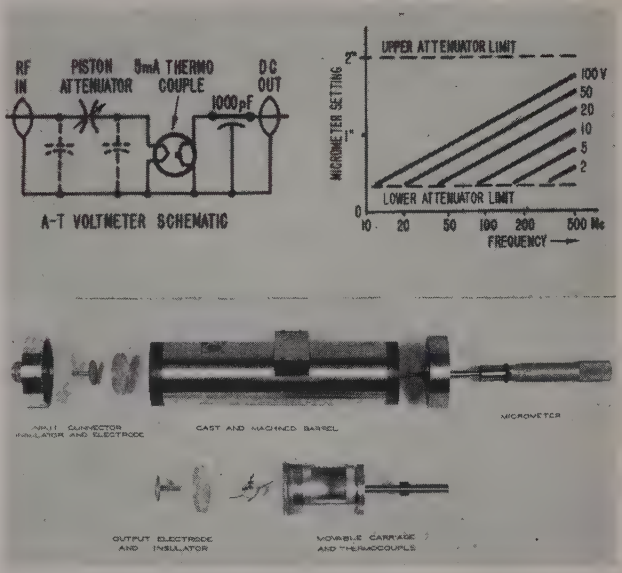


Fig. 5—NBS A-T voltmeter.

At high frequencies it is difficult to measure the harmonic content of signal sources. A good precaution, therefore, is to insert coaxial filters between the generator and micropotentiometer to discriminate against any possible harmonics. Transmission line effects can lead to much higher than expected voltages along a mismatched line. Since this effect is a function of frequency, harmonics will be affected to a greater extent than the fundamental signal voltage. For this reason the interconnections should be made as short as possible and the transmission line from the generator to the micropotentiometer should be approximately matched.

The HF transfer standard and schematic are shown in Fig. 4. The unknown ac voltage is applied to the probe and the galvanometer is balanced. Then the probe is plugged into the dc receptacle of the instrument case and rebalanced. The unknown ac is now equal to the dc required for rebalancing.

The A-T voltmeter and its schematic are shown in Fig. 5. The waveguide-below-cutoff attenuator is machined from a special casting, then honed, plated

and lapped to a final finish. Also shown is a sketch of the sensitivity curves of an A-T voltmeter as a function of frequency.

Both the HF transfer standard and the A-T voltmeter operate on the same principle of generating a thermocouple current proportional to an unknown input voltage, and they are both susceptible to the same calibration errors. Since both devices require input voltages in the order of 1 volt or more, they are not affected by the low-level effects of ground current errors. All other calibration errors, however, apply to the HF transfer standard and A-T voltmeter. In particular, we must consider critically the effects of transmission errors and response and waveform errors.

On any transmission line, the magnitude of the voltage will vary as a function of the distance along the line unless the line is terminated in its characteristic impedance. If we use a section of coaxial line to connect the unknown voltage to the HF transfer standard or A-T voltmeter, the capacitive loading imposed on the line by the voltmeter will cause the voltage to rise or fall relative to the point of unknown voltage. The magnitude of this change is determined not only by the input capacitance of the HF transfer standard or A-T voltmeter, but also by the frequency, the characteristics of the line itself and its length. The input capacitance used in determining this voltage change should be measured at the frequencies of interest rather than using an LF value since the two will often be considerably different. For example, at 700 Mc the input capacitance of an A-T voltmeter is approximately 5.1 pf, as compared to an LF value of 4.2 pf. If the A-T voltmeter is now connected to the unknown voltage by only 1 cm of 50-ohm line, the indicated voltage at 700 Mc will be 20 per cent in error.

In most applications the HF transfer standard or A-T voltmeter are used to calibrate another instrument. This usually means another transmission line to consider at high frequencies. For example, the standard voltmeter and the device to be calibrated may be interconnected to a generator with a T-adapter. If we consider the center of the adapter to be a point of reference, there will be a rise in voltage along both lines feeding the two voltmeters because of the unmatched termination.

To minimize this error at high frequencies, it is absolutely necessary to reduce the length of interconnecting line to as close to zero as possible. One method for accomplishing this is shown in Fig. 6. Here we are using the A-T voltmeter to standardize a diode-type voltmeter. The inputs to the two instruments are actually butted together, with the center conductor of the coaxial line feeding both voltmeters brought to their junction in the form of a flat insulated tab. Such a termination will produce large variations in voltage along the input coaxial line but, regardless of these variations, the two voltmeters will see as close to the same voltage as possible.

Another important source of calibration error when using either the HF transfer standard or A-T voltmeter is that caused by waveform distortion. Both voltage

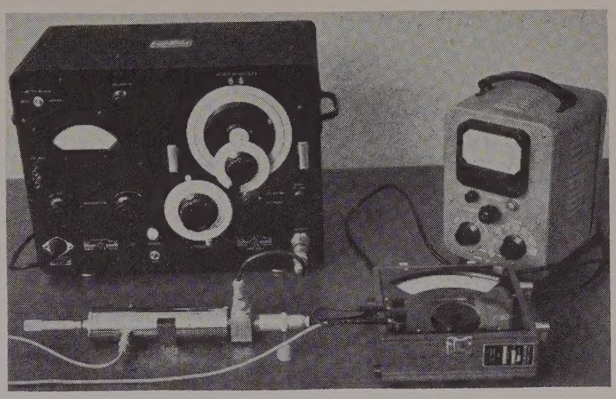
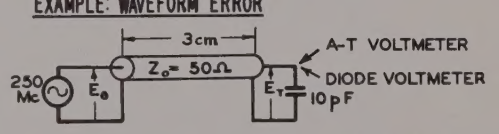


Fig. 6.

standards depend on the heating effect of vacuum thermocouples and, therefore, are rms-responding devices. If we use them to standardize working instruments that are other than rms-responding, serious errors can occur. In addition, transmission-line effects can seriously alter the harmonic content of the signal.

Consider again the test setup shown in Fig. 6. Assume that the generator is operating at a fundamental frequency of 250 Mc and has one per cent third harmonic and one per cent fifth harmonic. Assume further that we shorten the connecting cable between the generator and the VTVM being calibrated to only 3 cm. The connecting cable is assumed to have a 50-ohm characteristic impedance and to be terminated in a capacitive load of 10 pf representing the combined input capacitance of the A-T voltmeter and the diode-type voltmeter. As shown below, this set of conditions results in a signal being applied to the two voltmeters that now has approximately 5 per cent third harmonic and 0.4 per cent fifth harmonic. The large third harmonic will cause only a 1 per cent error in the rms responding A-T voltmeter but, depending on the phase relationships, can cause up to a 5 per cent error in the response and, therefore, the calibration of the peak responding voltmeter.

EXAMPLE: WAVEFORM ERROR



$$E_0 = A \sin \omega t + 0.01A \sin (3\omega t + \theta_1) + 0.01A \sin (5\omega t + \phi_1)$$

$$\frac{E_T}{E_0} = \frac{1}{\cos 1^\circ - \omega C Z_0 \sin 1^\circ} \qquad 1^\circ = 360\,\frac{1}{\lambda}$$

frequency	$1^\circ = 360\ 1/\lambda$	$\omega C Z_0$	$\cos 1^\circ$	$\omega C Z_0 \sin 1^\circ$	E_T/E_0
250 Mc	9	0.785	0.988	0.122	1.17
750	27	2.36	0.891	1.07	5.45
1250	45	3.92	0.707	2.77	0.45

$$\frac{E_T}{1.17} = A \sin (\omega t + \alpha) + 0.047A \sin (3\omega t + \theta_2) + 0.004A \sin (5\omega t + \phi_2)$$

Now, since A-T voltmeter is frequency sensitive (6 db/octave), the thermocouple current will be proportional to the fundamental and three times the magnitude of the 3rd harmonic. The rms indication of the A-T VTVM will be $\text{rms} = \sqrt{A^2 + (0.047 \cdot 3A)^2} \approx 1.01$ for 1 per cent error. The peak indication of the diode voltmeter will be, depending on the phase relationship, from 0 to 5 per cent in error.